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Fracture toughness of highly deformable polymeric materials

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Abstract

A fundamental requirement for safety design of structural components is flaw tolerance. In this field, the soft materials have a unique ability to bear external loads despite the presence of defects, due to their pronounced deformability. Unlike traditional materials, which have an enthalpic elasticity, the mechanical response of a polymer-based material is governed by the state of internal entropy of a molecular network which has a great ability to rearrange the material structure and shape so to minimize the local detrimental effect of flaws. For a correct estimation of the fracture toughness of these materials, a proper knowledge of this entropic effect is needed. In the present research, the mechanical behaviour up to failure of silicone-based cracked plates is examined by taking into account the time-dependent effects. Experimental and theoretical aspects are discussed in order to understand the defect tolerance of such materials.

Keywords: Fracture Mechanics; Polymer network; Fracture toughness; Damage tolerance

1. Introduction

Fracture toughness is an important property to be taken into account for defect tolerance-based design of structural components. Such a property quantifies the ability of a material to reduce the effect of flaws on the global strength of the structures. In this paper, we present the results of some experimental tests performed on flawed specimens made by a common silicone-based polymer. This material has a particular stress-strain curve, which is nearly hyperelastic up to failure, with a negligible effect of plasticity or internal damage until the final brittle failure occurs (Brighenti 2016).

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Nomenclature

$2a$	Initial crack length
$c(a)$	Decreasing function of a that reduces the actual applied remote stress during crack growth
E,ν	Young modulus and Poisson's ratio of the material, respectively
G	Energy release rate
K_I	Stress-Intensity Factor (SIF) in Mode I
K_I^*	Dimensionless Stress-Intensity Factor in Mode I
L_{cr}	Final crack length, measured along the crack path, after the final failure
t	Thickness of the specimen
W	Plate width
$\alpha = 2a/W$	Dimensionless crack length
γ	Fracture energy per unit cracked surface
$\dot{\varepsilon}$	Strain rate
η	Average radius of the micro voids existing in the material
λ	Stretch ratio
λ_S	Surface stretch
Ψ,Ψ_{el}	Total deformation energy and elastic energy, respectively
$\boldsymbol{\sigma},\sigma_{ij}$	Cauchy stress tensor
σ_∞	Remote applied stress

The mechanical behaviour of a polymeric material is quite different from that of a crystalline material (Doi 2013). As a matter of fact, in the absence of external forces, the microstructure of a crystal is in a stable equilibrium state that minimizes the energy of the system. The external forces produce displacements of the molecules and lead to a new equilibrium state with an increment of internal energy equal to the external work (in absence of non-conservative forces). This behaviour is called "enthalpic elasticity" because it's governed by internal energy. A polymer has a microstructure which is not made of crystalline units, but is characterized by a network of long molecular chains entangled all together. In absence of external forces, each chain is in a thermodynamical equilibrium state, i.e. the effective shape of the chain is one of the infinite possible configurations that the material can have for the current energy level.

The absolute temperature and the end-to-end distance of a chain defines its internal energy, while the energy of the unit volume of the material is obtained by adding up the energy of a single chain weighted by the probability density function of the chains' end-to-end distance distribution. It is clear why this kind of behaviour is called "entropic elasticity": the configuration of a chain is known only in probabilistic term, and it is ruled by the order of the system. Physically, the effect of external forces is to stretch the macromolecule in the direction of the applied load; mathematically, the external forces "stretch" the density probability function and the states with longer chains aligned in the load direction become more probable than before the deformation (Treloar 1973).

In the vicinity of a defect like a crack or a notch, the stress level abruptly increases within a narrow region close to the crack tip or notch root, and the chains are very stretched in the traction direction. Moreover if the external load slowly increases in time, the polymeric chains have the possibility to rearrange and change their shape without varying the global energy (Flory 1989). In fact, the part of the polymeric network close to the crack tip is in a much more ordered state with respect the other regions far from the crack because of the chains alignment. For a polymer network, fracture mechanics is ruled by non-local phenomena, and the conventional intensification of stress loses importance. Further, fracture toughness greatly depends on the strain rate because of the time-dependent phenomena occurring at the nanoscale level.

In the present paper, the fracture toughness is measured from some experimental tests made on polymer-based cracked plates. The values obtained are related to the strain rate and to the geometry of the specimen. Moreover, the evaluation of the fracture energy allows us to determine the intrinsic defect size through the use of the cavitation criterion to assess failure.